



## DFT Structural Analysis of Chamazulene

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**Abstract:** A combined theoretical and experimental study on the structure, infrared, UV-Vis, <sup>1</sup>H and <sup>13</sup>C NMR data of chamazulene is presented. Theoretical geometry optimizations and some additional properties of chamazulene and their IR, UV-Vis, NMR spectra were calculated using the DFT B3LYP /6-31G(d) level. Calculations were done using software Spartan 10. Experimental data showed that chamazulene have absorption maximum at 340 nm to 530 nm. The position of max did not much differ from the theoretically calculated value. The calculated density of states showed excellent agreement with UV/Vis diffuse reflectance spectra predicting the absorption maximum at 310 nm (calculated 332 nm) to 530 nm (calculated 516 nm). The IR normal modes were assigned for the two very small sp<sup>2</sup> CH valence bands and strong sp<sup>3</sup> CH vibrations. The aromatic overtone vibrations can hardly be detected and also the C=C vibration is very weak. <sup>1</sup>H NMR spectroscopy, showed resonances of the ring protons between 7 and 8 ppm. The methyl groups and the methylene group appear rather deshielded at 2.7 and 2.9 ppm. The calculations yielded reliable results that were in good correlation with experimental data. This study is a good basis for collaboration between experimentalists and quantum chemists.

## INTRODUCTION

Chamazulene (1,4-dimethyl-7-ethylazulene) is an aromatic chemical compound obtained by steam distillation of a variety of plants including chamomile (*Matricaria chamomilla*), wormwood (*Artemisia absinthium*), and yarrow (*Achillea millefolium*). It is a blue-violet derivative of azulene which is synthesized from the sesquiterpene matricin (Meisels and Weizmann 1993; Özgür, Cemal, Senyel 2009). For the quantitative determination of essential oil, total azulenes and chamazulene in chamomile, various methods are used, such as gravimetry, spectrophotometry in the visible region and gas chromatography (Peters, Lanzilotta, Lemon, et al., 1998). Density Functional Theory (DFT) has been accepted by the quantum chemistry community as

reliable and effective approach for the computation of molecular structure, vibration frequencies and energies of chemical reactions (Beyramabadi and Morsali 2011; Kadhum, Al-Amiery, Shikara, et al., 2011). DFT calculations provide an excellent agreement with experimental vibrational frequencies of investigated compounds. These calculations have been used extensively for calculating a wide variety of molecular properties such as equilibrium structure, charge distribution. Ultraviolet-visible spectroscopy (UV/Vis), Infrared frequencies (IR) and Nuclear Magnetic Resonance (NMR) spectra, and provide reliable results which are in agreement with experimental data (Becke, 1993). The purpose of this work is to determine the chamazulene of essential oil from Bosnia and Herzegovina chamomile samples by Thin Layer Chromatography (TLC) and UV/Vis method. Furthermore, chamazulene was characterized theoretically and experimentally by IR, UV-Vis and NMR

spectroscopy. The Beck's three-parameter exchange functional with the Lee, Yang and Parr correlation functional (B3LYP), developed by Truhlar et al. were used to perform theoretical calculations of the investigated compound (Lee, Yang, Parr, 1988; Zhao, Y., Truhlar, 2005).

## MATERIAL AND METHODS

### Materials

Chamomile tea commercially available from Bosnian markets was used in this study. All the reagents and chemicals were purchased from Sigma-Aldrich Co. LLC.

### Investigated compounds

The compound chamazulene was studied for their experimental and theoretical properties. Structure of investigated compound is presented in Figure 1.

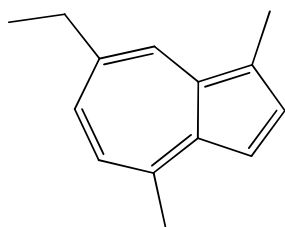


Figure 1: Structure of chamazulene

### UV-Vis and TLC analysis

The methods for chamazulene determination in chamomile essential oil was developed based on silica gel G TLC and UV-spectrophotometry.

The chamazulene was isolated from chamomile by steam distillation and extracted with methyl tert-butyl ether (3 × 100 mL). The combined extracts are dried over MgSO<sub>4</sub>, filtered and the solvent is removed in vacuo. The sample was dissolved in ethanol and applied to pre-coated TLC. The chromatographic separations were done on the silica gel F254. TLC plates developed with dichloromethane: ethylacetate (9:2 v/v). Detection was performed under UV lamp at 254 nm and the evaluation of the chromatographic plate was based on processing of chromatographic images. Then R<sub>f</sub> value was calculated and compared with literature data (Padula, Rondina and Coussio 1976; Roth and Rupp 1995).

Ultraviolet Spectra were recorded using LAMBDA 25, PerkinElmer UV-Vis Spectrometer, and ethanol was used as solvent for the dilution of sample as well as blank.

### Theoretical calculations

All the calculations were carried out with the Spartan 10 software. The geometries were optimized using the method: B3LYP basis set: 6-31G(d) as shown in Figure 2. The harmonic vibration frequencies were calculated by this method and the results were compared with experimental spectra. This method was used for calculating IR, UV-Vis and NMR spectra at the B3LYP/6-31G (d) level for chamazulene.

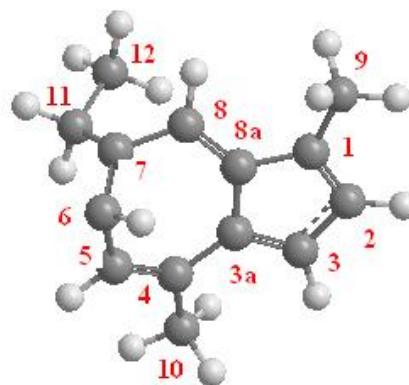


Figure 2. The optimized geometry of the chamazulene

## RESULTS AND DISCUSSION

### TLC and UV/Vis data of the prepared chamazulene

TLC study of the isolated compound was found (R<sub>f</sub>=0.80) almost similar to that of the literature (R<sub>f</sub>=0.78) data so this study concludes that the isolated compound may be chamazulene. Chamazulene was determined directly by measuring absorbance at 310 nm to 530 nm.

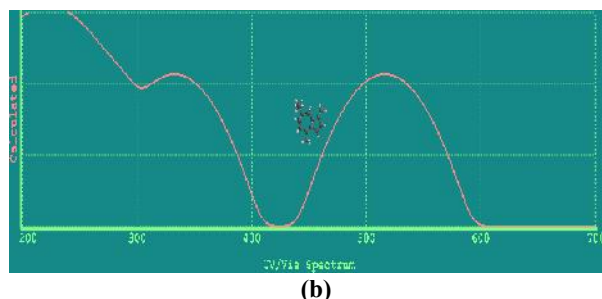
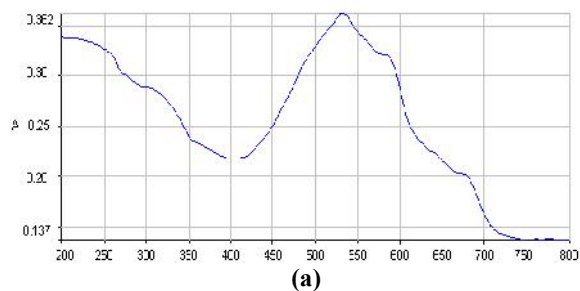
### Experimental and theoretical UV/Vis spectral data

The electronic spectra of the chamazulene exhibit two characteristic broad bands at 340 nm and 530 nm (Table 1).

Table 1. Experimental and theoretical UV/Vis spectral data for chamazulene

Compound	$\lambda_{\max}$ [nm] (Exp.)	$\lambda_{\max}$ [nm] (Calcd.)	Intensity
Chamazulene	225	228	1.1687
	266	264	0.0529
	340	332	0.0184
	530	516	0.0183

The chamazulene exhibits the absorption maximum at 340 nm to 530 nm (Figure 3a). The position of  $\lambda_{\max}$  did not much differ with theoretical calculation (Figure 3b). The calculated density of states showed excellent agreement with UV-Vis diffuse reflectance spectra predicting the absorption maximum at 310 nm (calculated 332 nm) to 530 nm (calculated 516 nm). The calculated values are lower than the experimental absorption maximum (Table 1). The reason for the discrepancies between the theory and experiment can be the vibrational effects, which are not taken into account and hydrogen bonding with the solvent molecules. The correlation factor from the linear regression was 0.9997.



**Figure 3:** Experimental (a) and theoretical (b) calculation of UV/Vis absorption spectra of chamazulene

#### Experimental and theoretical IR spectral data

The results of the calculated and experimental harmonic frequencies of chamazulene are collected in Table 2.

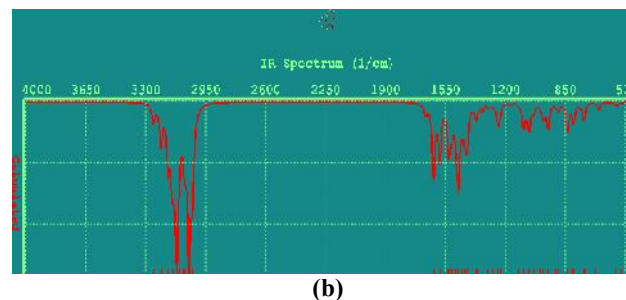
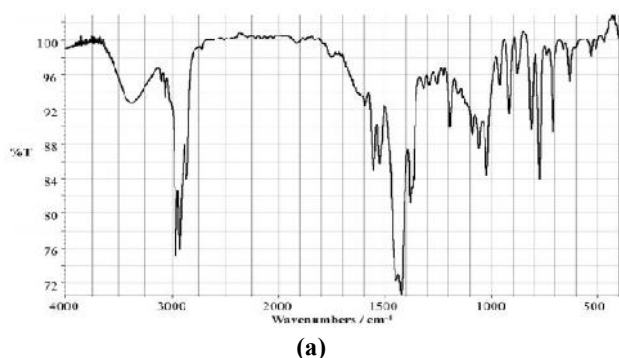
**Table 2.** Experimental and theoretical IR spectral data ( $\text{cm}^{-1}$ ) for chamazulene

vibrations	$\nu_{\text{exp.}}^*$ [ $\text{cm}^{-1}$ ]	$\nu_{\text{calcd.}}$ [ $\text{cm}^{-1}$ ]
$\text{sp}^2$ CH	3200	3170
$\text{sp}^3$ CH	3000	3027
C=C	1600	1620

\* Experimental values from literature (Berger and Sicker 2009)

Theoretical IR spectra of chamazulene shows similar characteristic infrared band frequencies. The correlation factor from the linear regression was 0.9990.

Chamazulene gives the two very small  $\text{sp}^2$  CH valence bands at about  $3200 \text{ cm}^{-1}$  (calculated  $3170 \text{ cm}^{-1}$ ) and strong  $\text{sp}^3$  CH vibrations below  $3000 \text{ cm}^{-1}$  (calculated  $3027 \text{ cm}^{-1}$ ). The C=C vibration at  $1600 \text{ cm}^{-1}$  (calculated  $1620 \text{ cm}^{-1}$ ) is very weak displayed in Figure 4.



**Figure 4:** Experimental values from literature (Berger and Sicker 2009)(a) and theoretical (b) calculation of IR spectra of chamazulene

#### Experimental and theoretical NMR spectral data

Chemical shifts calculated using the B3LYP level with the 6-31G (d) basis sets can be utilized to eliminate the uncertainties in the fundamental assignments of the spectra. The  $^1\text{H}$  and  $^{13}\text{C}$  theoretical and experimental chemical shifts, isotropic shielding tensors and assignments of chamazulene are presented in Tables 3 and 4, respectively.

#### DFT calculations for structural and electronic properties

Optimized molecular structures of chamazulene of the most stable form are shown in Figure 2. Molecular orbital calculations provide a detailed description of orbitals including spatial characteristics, nodal patterns and individual atom contributions.

**Table 3.** The experimental and calculated  $^1\text{H}$ -isotropic chemical shifts, ppm, with respect to  $\text{SDCl}_3$  for chamazulene

Assignment	Chemical shift $\delta$ (ppm)	
	(Exp.)*	(Calcd.)
H2	7.62	7.49
H3	7.22	7.04
H5	6.98	6.92
H6	7.39	7.50
H8	8.16	8.12
H9	2.66	2.51
H10	2.83	2.66
H11	2.85	2.81
H12	1.35	1.34

\* Experimental values from literature (Berger and Sicker 2009)

The aromatic ring gave resonances in the region from 7.0–8.0 ppm in the  $^1\text{H}$  NMR spectra of chamazulene. The edited  $^{13}\text{C}$  NMR spectrum displays in the aromatic region five CH signals and five signals of quaternary carbons; from the carbon spectrum alone. The calculated and experimental chemical shift values showed good correspondence. The correlation factors for  $^1\text{H}$  NMR is 0.9989 and  $^{13}\text{C}$  NMR is 0.9952.

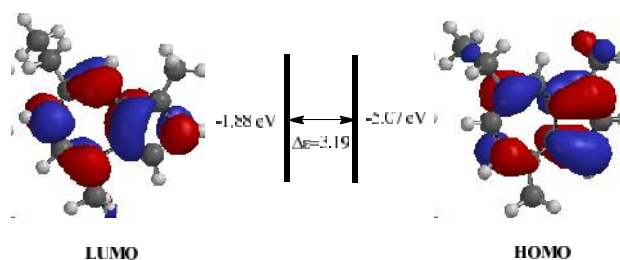
**Table 4.** The experimental and calculated  $^{13}\text{C}$ -isotropic chemical shifts, ppm, with respect to  $\text{SDCl}_3$  for chamazulene

Assignment	Chemical shift $\delta$ (ppm)	
	(Exp.)*	(Calcd.)
C1	137.4	138.08
C2	136.2	131.15
C3	112.8	105.87
C3a	136.2	129.38
C4	144.3	138.17
C5	125.0	119.01
C6	136.4	130.12
C7	135.7	129.20
C8	134.7	129.43
C8a	125.1	130.40
C9	12.9	14.39
C10	24.1	25.70
C11	33.8	37.50
C12	17.4	20.78

\* Eksperimental values from literature (Berger and Sicker 2009)

The contour plots of the frontier orbitals for the ground state are shown in Figure 5, including the Highest Occupied Molecular Orbital (HOMO) and Lowest Unoccupied Molecular Orbital (LUMO). The both orbitals are substantially distributed over the conjugation plane. It can be seen from the Figure 5 that the HOMO orbitals are located on the substituted molecule while LUMO orbitals resemble those obtained for the unsubstituted molecule and therefore the substitution has an influence on the electron donation ability, but only a small impact on electron acceptance ability. It can be seen that the energy gaps between HOMO and LUMO of chamazulene is 3.19 Hartree. The values of the HOMO and LUMO energy gap explained the eventual charge transfer interaction taking place within the molecules. The lower the HOMO–LUMO energy gap, the lighter and

less stable/more reactive the molecule (Kadhum, Mohamad, Al-Amiery, et al., 2011).

**Figure 5:** Frontier molecular orbitals of chamazulene

The energy gaps between HOMO and LUMO of guaiazulene is 3.20 Hartree (Safayhi, Sabieraj, Sailer, et al., 1994). Chamazulene is more reactive than guaiazulene (Špirtović-Halilović, S., Salihović, M., Osmanović, et al., 2014) because it has lower value of the HOMO and LUMO energy gap.

### Atomic charges for chamazulene

Atomic charges of chamazulene showed in Table 5. These data show that the atomic charge has been affected by the presence of substituent of rings (Kadhum, Al-Amiery, Shikara, et al., 2011; Kadhum, Wasmı, Mohamad, et al., 2012) as shown in the Table 5.

The data (Table 5.) show that the high estatomic charge in molecule is at [C(3) -0.418] and the next charge value is at [C(5) -0.249]. These data show clearly that these two atoms are the most reactive toward the substitution reactions.

**Table 5.** Atomic charges of chamazulene

Atom	Atom type (MM2)	Charge Huckel	Atom	Atom type (MM2)	Charge Huckel	Atom	Atom type (MM2)	Charge Huckel
C(1)	C Alkene	-0.095	C(13)	C Alkane	0.184	H(25)	H	0.047
C(2)	C Alkene	-0.0434	C(14)	C Alkane	-0.109	H(26)	H	0.248
C(3)	C Alkene	-0.418	H(15)	H	0.028	H(27)	H	0.035
C(4)	C Alkene	-0.074	H(16)	H	0.028	H(28)	H	0.036
C(5)	C Alkene	-0.249	H(17)	H	0.286	H(29)	H	0.042
C(6)	C Alkene	0.249	H(18)	H	0.029	H(30)	H	0.043
C(7)	C Alkene	0.142	H(19)	H	0.021	H(31)		
C(8)	C Alkene	0.417	H(20)	H	0.037			
C(9)	C Alkene	-0.177	H(21)	H	0.040			
C(10)	C Alkene	-0.182	H(22)	H	0.041			
C(11)	C Alkane	-0.146	H(23)	H	0.039			
C(12)	C Alkane	-0.15	H(24)	H	0.046			

## CONCLUSIONS

Selected structural parameters of the optimized geometries of the chamazulene have been obtained by DFT calculations. The electronic spectra of the chamazulene fundamental modes have been precisely assigned and analyzed and the theoretical results were compared with the experimental values. Conducted research provides data about electronic spectra and structural information of chamazulene. The calculations yielded reliable results that were in good correlation with experimental data. This study is a good basis for collaboration between experimentalists and theoretical chemists.

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### Summary/Sažetak

Predstavljena je kombinovana teorijska i eksperimentalna studija strukture, IR, UV-Vis,  $^1\text{H}$  i  $^{13}\text{C}$  NMR spektara hamazulena. Teorijska geometrijska optimizacija i neka molekulska svojstva hamazulena kao i njegovi IR, UV-VIS, NMR spektri su izračunati pomoću DFT B3LYP / 6-31G(d) niva. Proračuni su urađeni pomoću softvera Spartan 10. Eksperimentalni podaci pokazuju da hamazulen ima maksimum apsorpcije na 340 nm do 530 nm. Položaj  $\lambda_{\text{max}}$  se ne razlikuje mnogo od teorijsko dobivenog. Maksimum apsorpcije za hamazulen je dobiven na 310 nm (izračunato 332 nm) i na 530 nm (izračunato 516 nm) što pokazuje odlično slaganje. Na IR spektru hamazulena se vide dva jako mala apsorpciona maksimuma koji potiču od vibracija istezanja  $\text{sp}^2$  CH veze i jaki koji potiče od vibracija istezanja  $\text{sp}^3$  CH veze. Apsorpcioni maksimum koji potiče od aromatskih vibracija teško se može otkriti, a za C=C vibracije je vrlo slab.  $^1\text{H}$  NMR spektroskopija, pokazala je signaleza protone prstena između 7 i 8 ppm. Signali protona metilne i metilenske grupe uočeni su na 2.7 and 2.9 ppm. Nađeno je da su rezultati pouzdani i u dobroj saglasnosti sa eksperimentalnim podacima. Ova studija je dobra osnova za saradnju između eksperimentatora i kvantnih hemičara